Commentary

Towards a Conceptual Framework for Restoration Ecology

Abstract

Heightening human impacts on the Earth result in widespread losses of production and conservation values and make large-scale ecosystem restoration increasingly urgent. Tackling this problem requires the development of general guiding principles for restoration so that we can move away from the ad hoc, site- and situation-specific approach that now prevails. A continuum of restoration efforts can be recognized, ranging from restoration of localized highly degraded sites to restoration of entire landscapes for production and/or conservation reasons. We emphasize the importance of developing restoration methodologies that are applicable at the landscape scale. Key processes in restoration include identifying and dealing with the processes leading to degradation in the first place, determining realistic goals and measures of success, developing methods for implementing the goals and incorporating them into land-management and planning strategies, and monitoring the restoration and assessing its success. Few of these procedures are currently incorporated in many restoration projects. The concept that many ecosystems are likely to exist in alternative stable states, depending on their history, is relevant to the setting of restoration goals. A range of measures, such as those being developed to measure ecosystem health, could be used to develop "scorecards" for restoration efforts. Generalizable guidelines for restoration on individual sites could be based on the concepts of designed disturbance, controlled colonization, and controlled species performance. Fewer explicit guidelines are available at the landscape scale, beyond nonquantitative generalities about size and connectivity. Development of these guidelines is an important priority so that urgent large-scale restoration can be planned and implemented effectively.

Introduction

There has been a tremendous upsurge in interest in restoration as a technique for reversing habitat degradation world-wide (Cairns 1988; Jordan et al. 1988; Hobbs 1993; Saunders et al. 1993*a*). Restoration ecology has been hailed as a new paradigm for biological conservation (Jordan 1994; Turner 1994), although other authors point out the many practical problems still to be overcome (Barrett 1994; Gorchov 1994; Loucks 1994; Medley 1994). Allen & Hoekstra (1992) commented that "Restoration ecology has, until recently, been seen as a sort of gardening with wild species in natural mosaics." Kirby (1994) went so far as to assert that "Restoration ecology is an expensive self-indulgence for the upper classes, a New Age substitute for psychiatry. It distracts intelligent and persuasive people from systemic initiatives."

What is clear is that restoration ecology has largely progressed on an ad hoc, site- and situation-specific basis, with little development of general theory or principles that would allow the transfer of methodologies from one situation to another. This is illustrated at the international level by the editorial by Majer & Recher (1994), which shows little cross-fertilization of ideas between different localities. We consider this to be inappropriate in today's climate of urgent needs for large-scale ecosystem restoration and rehabilitation. We feel that it is essential that generalities be sought and principles be generated so that restoration efforts

can be guided effectively. This paper identifies some of the key principles and generalities that might be used to formulate a conceptual framework for restoration ecology. We draw most of our examples from terrestrial systems but believe that the points raised will also be generalizable to aquatic and marine systems.

What is Restoration Ecology?

Ecologists seem to take perverse delight in developing complex terminologies. The ensuing ecological verbiage is of doubtful value, especially when there is little general agreement on correct usage. This is certainly true in the field of restoration ecology, where the terms restoration (with the qualifiers sensu stricto and sensu lato; Aronson et al. 1993*a*), rehabilitation, reallocation, reconstruction, and many others are used differently or interchangeably depending on whose paper you read. A stable terminology would undoubtedly be useful, but no one currently seems prepared to agree on one. We suggest that endless quibbling over what to call our work in the field of restoration ecology is a time-wasting diversion from the real work at hand.

Rather than descend into a nomenclatural quagmire and argue over the meaning of particular terms, we find it more instructive to emphasize the idea that restoration occurs along a continuum and that different activities are simply different forms of restoration. Here, we examine the different types of situation in which restoration ecology is used. Restoration is usually carried out for one of the following reasons:

(1) To restore highly degraded but localized sites such as mine sites. Restoration often entails amelioration of the physical and chemical characteristics of the substrate and ensuring the return of vegetation cover. (Collins et al. 1985; Bradshaw 1987; Ward et al. 1990; Schaller 1993).
(2) To improve productive capability in degraded production lands. Degradation of productive land is increasing worldwide, leading to reduced agricultural, range, and forest production. Restoration in these cases aims to return the system to a sustainable level of productivity, for example by reversing or ameliorating soil erosion or salinization problems in agricultural or range lands (= rehabilitation; Aronson et al. 1993*a*).
(3) To enhance conservation values in protected landscapes. Conservation lands worldwide are being reduced in value by various forms of degradation, including the effects of introduced stock, invasive species (plant, animal, and pathogen), pollution, and fragmentation. In these cases, restoration aims to reverse the impacts of these degrading forces, for example by removing an introduced herbivore from a protected landscape.
(4) To enhance conservation values in productive landscapes. In addition to the need for restoration efforts within conservation lands, there is also a need to increase the area of natural or seminatural vegetation in regions where habitat loss and fragmentation have been extensive. There is an increasing recognition that protected areas alone will not conserve biodiversity in the long term, and that methods of integrating conservation and productive use must be achieved (Hobbs 1993; Morton et al. 1995). Restoration in this case entails returning conservation value to portions of the productive landscape, preferably through an integration of production and conservation values.

The application of restoration ecology thus occurs along a continuum from the rebuilding of totally devastated sites, such as those associated with mining, to the limited management of relatively unmodified sites (Hobbs & Hopkins 1990). The manner in which restoration ecology is applied to these different situations is fundamentally similar, although the goals for each and the techniques used will obviously differ. In each case, restoration aims to return the degraded system to some

form of cover that is protective, productive, aesthetically pleasing, or valuable in a conservation sense. A further tacit aim is to develop a system that is sustainable in the long term. The recognition of this continuum of activities bundled together under the banner of restoration ecology clears away much of the confusion over what restoration ecology actually is. In this paper we concentrate mostly on the third and fourth types of activities described above, although our comments are relevant to the entire spectrum of restoration ecology.

These considerations involve a move away from the traditional view of restoration as a site-by-site activity to one in which restoration occurs at a landscape scale and is an important component of landscape and regional planning (Naveh 1994). For example, landscape-scale restoration is essential if large-scale hydrological problems are to be dealt with effectively (Cohn 1994; George et al. 1995; Hey & Phillippi 1995). Landscape-scale restoration can also assist in integrating productive and nonproductive land uses. In the Western Australian wheatbelt, for example, extensive clearing of native vegetation has led to major habitat loss and to major hydrological changes resulting in serious soil salinity problems. Restoration plantings are being widely undertaken to address the hydrological imbalance, and these plantings also would have considerable potential for nature conservation if appropriate species were used (Hobbs & Saunders 1993).

We include productive lands in our continuum of restoration activities, in contrast to other recent definitions (Jackson et al. 1995), because we believe that productive and conservation lands have to be considered simultaneously in larger-scale restoration efforts. Restoration at the landscape scale will involve restoring a combination of some landscape components for productive purposes and some for conservation purposes. In this way we can combine several, or maybe all, of the key reasons for restoration in the same landscape. Allen & Hoekstra (1992) have presented the view that restoration ecology is restricted to one scale of activity and generally aims to fulfill a single criterion. We argue here that this need not be the case: indeed, if restoration ecology is to be a useful tool for land management it should operate across multiple scales and fulfill a range of criteria. Restoration projects planned at the landscape scale can become more than the sum of the individual site-based components. Restoration is, in fact, likely to be a key tool for ensuring integrated land management for production and conservation, a key component for the development of sustainable land-management systems. As such, it has much to offer worldwide, particularly in the most rapidly developing parts of the world (especially the tropics). Restoration also provides one of the most accessible ways in which local communities can become actively involved in nature conservation and see positive outcomes as restoration develops through time.

Key Processes in Restoration

We have identified a number of key processes in restoration ecology that we consider essential for the successful integration of restoration into land management:

(1) Identify processes leading to degradation or decline.
(2) Develop methods to reverse or ameliorate the degradation or decline.
(3) Determine realistic goals for reestablishing species and functional ecosystems, recognizing both the ecological limitations on restoration and the socioeconomic and cultural barriers to its implementation.
(4) Develop easily observable measures of success.
(5) Develop practical techniques for implementing these restoration goals at a scale commensurate with the problem.
(6) Document and communicate these techniques for broader inclusion in land-use planning and management strategies.

(7) Monitor key system variables, assess progress of restoration relative to the agreed-upon goals, and adjust procedures if necessary.

We suggest that, currently, restoration activities frequently occur with little or no consideration of these processes. We argue that restoration measures often proceed without initial identification and reversal or amelioration of the processes causing the degradation. Such restoration projects are doomed to failure because the degrading influences will continue to operate and work against restoration efforts. Failed restoration projects not only waste resources but lead to disillusionment among those trying to implement them. Also, many restoration projects proceed with only the broadest of objectives, often with little consideration of whether these objectives are attainable, and with no means of assessing the degree to which the objectives have been met. Methodologies developed for restoration projects also have been largely ad hoc and site-specific, and there has been little attempt to generalize from one site or system to another (Berger 1990) or to conduct restoration across entire landscapes. Similarly, there has seldom been much effort directed at incorporating restoration into broader land-use management and planning strategies.

We argue that these steps are essential if ecological restoration is to develop into a useful and widely applicable science. Here we explore a set of ecological principles, associated with these key processes, that might guide the development of restoration ecology in this direction.

Reversing the Causes of Ecosystem Degradation

As we noted earlier, many human activities lead to the degradation of ecosystems, either intentionally or inadvertently. Degrading processes can result in a variety of ecosystem responses, depending on the intensity, duration, and scale of the impact. Brown & Lugo (1994) have also recently pointed out that the impact of degrading influences, or stressors, varies depending on which system components and processes are affected (Fig. 1a). Stressors that affect the processes of resource capture by plants (e.g., soil erosion, alteration of hydrology) are likely to have much greater effects than stressors that remove or damage plants or consumers (e.g., pathogens or unsuitable fire regime). The potential for reversal of stressors also depends on which components and processes are being affected. It will be easier to remove or control stressors that affect the biotic components of the system only than to reverse the effects of stressors on the resource base and the ability to capture resources (Fig. 1b). Cessation of the former type of stressor may result in ecosystem recovery without further management intervention (Allen et al. 1994), whereas cessation of the latter type is unlikely on its own to be sufficient (Milchunas & Lauenroth 1995).

Nevertheless, it is still possible that removing a stressor that affects only the biotic component will not result in ecosystem recovery if components of the original system have been lost. Similarly, if the effects on the biotic component have further effects on critical ecosystem processes, removal of the stressor will not be sufficient. It therefore becomes essential to recognize when restoration can be achieved by simple removal of stressors and when this alone will not be sufficient and further actions are needed. We next explore a possible theoretical framework for this assessment.

Alternative Stable States and Thresholds

The prevailing paradigm in restoration ecology involves returning a degraded system to some desired state by accelerating biotic change or reinitiating succes-

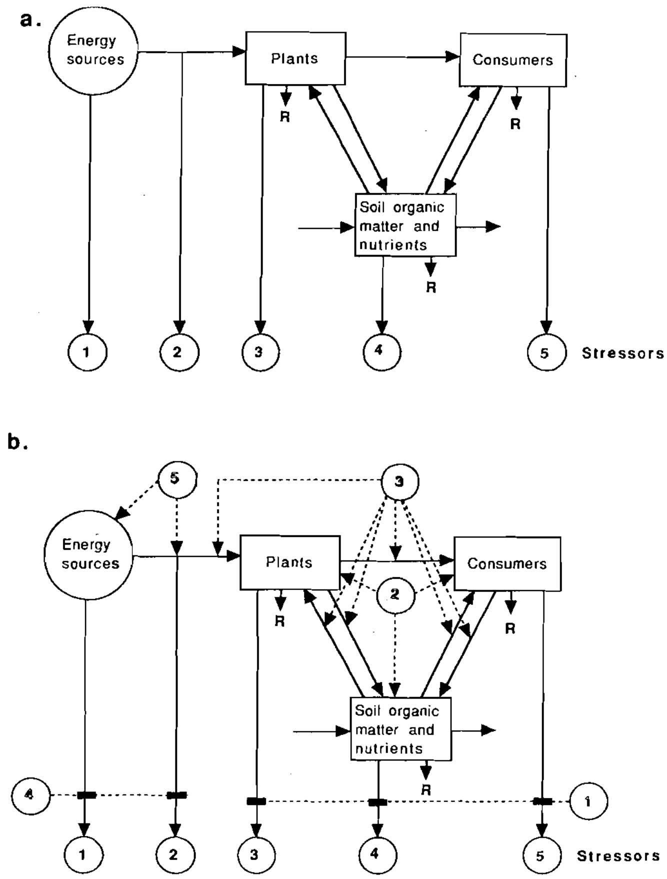

Figure 1. (a) Simplified model of an ecosystem, with resource inputs, major components, and flows, indicating where stressors (circles numbered 1–5) impact on the system. Stressors 1 and 2 have the greatest impact because they act on resource supplies, while stressors 3–5 act on biotic components. "R" represents respiration losses. (b) The same system indicating the actions needed to restore the degraded ecosystem (circles containing shadow figures). Options 1 and 4 involve removing the stressor, while options 2, 3, and 5 involve replacing lost ecosystem components. The degree of difficulty and cost of restoration increase from 1 to 5. Redrawn, with permission from Brown and Lugo (1994).

sional processes (Luken 1990; Edwards et al. 1993). The restoration process thus involves directing system development along a desired trajectory (Fig. 2). For instance, Aronson et al. (1993) defined restoration as "endeavors that seek to halt degradation and to redirect a disturbed ecosystem in a trajectory resembling that presumed to have prevailed prior to the onset of disturbance." Recently, however, it has been suggested that ecosystems may not always undergo more or less ordered and gradual development but may instead undergo rapid transitions between different metastable states (Westoby et al. 1989; Drake 1990; Hobbs 1994). Such transitions indicate nonlinear and threshold responses to management and environmental factors, with the occurrence of particular states depending on particular combinations of driving factors.

MacLeod et al. (1993), Ash et al. (1993), and Grice and McIntyre (1995) have recently employed conceptual models using the above state and transition approach to examine the restoration of degraded rangeland areas. Their approach considers transitions between different states driven by grazing pressures and other impacts and indicates that transitions leading to increased degradation may be easier to force than transitions desired to restore the systems, due to the presence of pronounced system thresholds (as discussed by Aronson et al. 1993a). Once

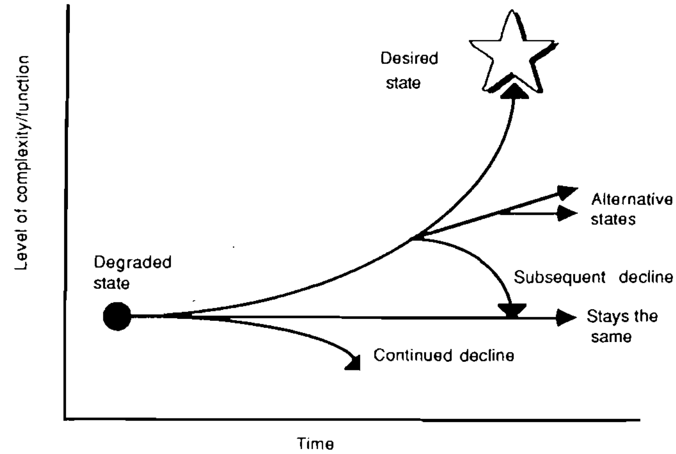

Figure 2. Traditional view of restoration options for a degraded system, illustrating the idea that the system can travel along a number of different trajectories and that the goal of restoration is to hasten the trajectory towards some desired state. In this view, the past history of the system is not considered, yet the route by which the system reaches the present point can have a large impact on the potential for restoration (Hobbs & Mooney 1993).

the system crosses such a threshold, it may require massive management inputs to restore it to its original condition (Fig. 3). Walker and Boyer (1995) have recently discussed a similar model for longleaf pine forest ecosystems in North America. We consider that this conceptual framework is generalizable to many other systems and provides a useful starting point for the development of restoration principles. Restoration can then be viewed as an attempt to force transitions towards a desired state, and as requiring knowledge of the variables that need to be manipulated to achieve these transitions. The recognition that alternative states are possible in any particular location, even under natural conditions, also provides cause for thought about the restoration goals to be set, especially with reference to defining "naturalness." Luh & Pimm (1993) have pointed out the possibility that restoration may produce a persistent community that may not be the "desired" community: "Even with all the species, we may be unable to reassemble communities."

As noted earlier, restoration of degraded systems depends on the removal of the influences leading to degradation. Often, however, the system will not respond directly to the removal of the degrading or stressing influence and will need some other intervention to facilitate restoration. In other words, removal of the degrading influence may often be necessary but not sufficient to promote restoration. The concept of thresholds allows a general explanation of this phenomenon. When the system is in a degraded state but has not crossed a threshold, removal of the degrading influence may be all that is required to encourage restoration. Thus, for instance, woodlands currently degraded by grazing may recover and regenerate simply by excluding stock. On the other hand, if the system has crossed a threshold, removing the degrading influence will not be sufficient to allow transition back to something approximating the original state. For instance, if the grazed woodland is heavily invaded by weeds and the soil structure is altered, removal of grazing will not be enough to promote woodland recovery. In the same way, rangelands severely degraded by stock grazing are unlikely to recover after simple removal of stock (MacLeod et al. 1993).

Hobbs (1996) has explored the idea that transitions between states may be more difficult if they involve changes in the composition of the ecosystem in terms of the functional groups represented. Thus, for instance, a change from grassland to a shrubland is more difficult to force than a change from one grassland type to an-

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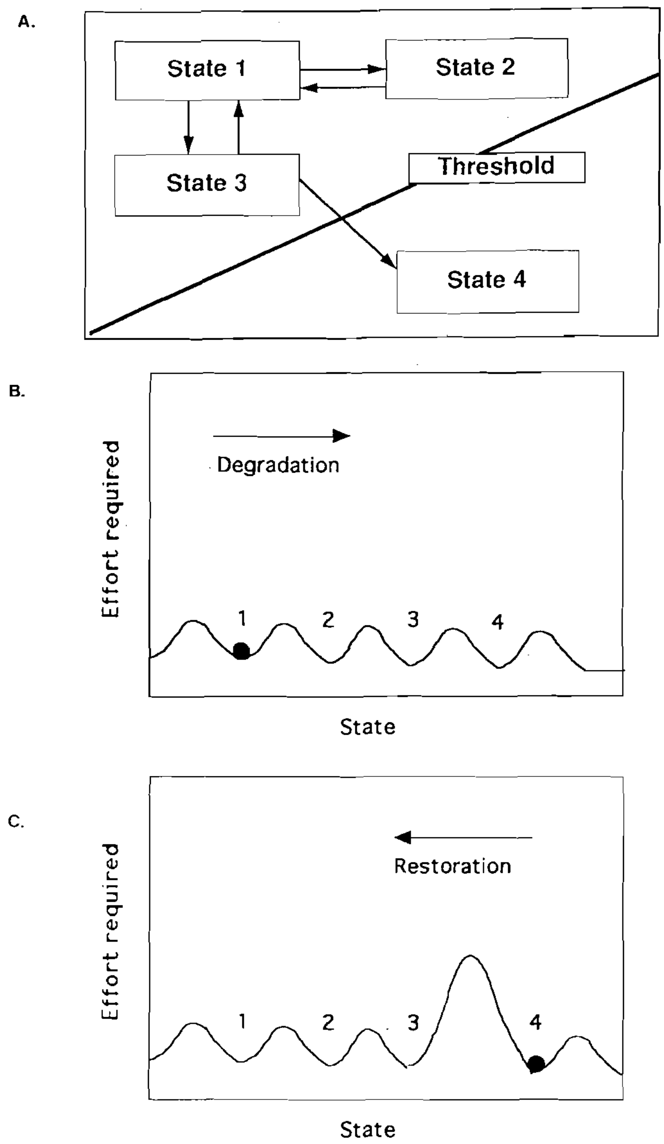

Figure 3. A state and transition approach to restoration. (a) A hypothetical system that can exist in four alternative stable states. State 1 is an undegraded state, states 2 and 3 are partially degraded, and state 4 is highly degraded. Transitions from state 1 to other states occur in response to different stressors or different levels of the same stressor. Transitions back from states 2 and 3 to state 1 are possible if the stressor is removed. But the transition from state 2 to state 4 involves crossing a threshold that precludes return to state 2 without increased management intervention, even if the stressor is removed. (b) and (c) Illustrations of the degree of effort required to force transitions between states. The process of degradation may force transitions that are much more difficult to force back during the process of restoration.

other (Hobbs 1994). This idea has relevance to restoration in that the presence of thresholds may be linked to the functional composition of the system. Rangelands normally dominated by perennial grasses are difficult to restore once they have been invaded by shrubs, while, conversely, range that is normally dominated by shrubs is essentially impossible to restore following invasion by annual grass (Whisenant 1990; MacLeod et al. 1993). Similarly, woodlands in Australia that have lost their shrub understory and have been invaded by annual grasses are difficult to restore (other examples are explored by Aronson et al. 1993*b*). In all

these cases, considerably more management input is required to return the system to a previous state. The question for restoration ecology is how to develop practical and cost-effective methods of forcing those transitions.

Ecosystem Attributes to be Restored

Ecosystem restoration seeks to return some aspects of the natural ecosystem to treated areas. Characteristics of natural ecosystems can be summarized as follows:

(1) composition: species present and their relative abundances;
(2) structure: vertical arrangement of vegetation and soil components (living and dead);
(3) pattern: horizontal arrangement of system components;
(4) heterogeneity: a complex variable made up of components 1–3—heterogeneity of soil characteristics, litter distribution, etc., may also be important;
(5) function: performance of basic ecological processes (energy, water, nutrient transfers);
(6) dynamics and resilience: successional processes, recovery from disturbance.

In any given landscape, a variety of different vegetation (or patch) types makes up a complex mosaic. Each type will have a characteristic set of attributes. The broad vegetation type that would have occurred in any particular area can often be inferred from landform, soil type, or other biophysical attributes. This then gives a first approximation to the type of vegetation that needs to be restored. Primary questions then to be addressed are how closely the attributes of natural ecosystems have to be reproduced for successful reconstruction and which are the important attributes? Aronson et al. (1993*a*) suggested a set of "vital ecosystem attributes" related to structure and function. Which attributes are the most important to restore? Can we, for instance, restore structure and function without necessarily restoring the same composition? Work by Ewel (1986) and Ewel et al. (1991) suggests that this may indeed be possible, which leads to the question of whether non-native species have any value in restoring some of the required attributes (Bridgewater 1990; Hobbs & Mooney 1993). Clearly, the answers to these questions will in large part be determined by the objectives set for the restoration. Restoration of productive capability in degraded land could be achieved in quite different ways from the restoration of conservation values.

Reference States and "Naturalness"

How closely the attributes of natural ecosystems have to be reproduced for successful restoration is an important consideration. Most definitions of restoration for conservation purposes focus on the idea of reestablishing what might have occurred on a site had it been undisturbed. Restoration efforts seek to restore damaged systems to a defined indigenous ecosystem that resembles the original in all respects. This strict definition of restoration is handicapped by ambiguous goals and criteria for success (Cairns 1989, 1991; Aronson et al. 1993*a*). Because we seldom understand the composition, structure, function, or dynamics of historic ecosystems, it is difficult to measure success against such models.

The idea of "natural" communities and ecosystems is commonly implied or stated explicitly, but what do we mean by natural in the context of today's systems, which have all experienced human impact to a greater or lesser degree? Concepts of what is natural vary across the globe, depending on the length of human habitation in the area, and, in the New World, the time since European colo-

nization. In some parts of the world, it is still possible to find tracts of land largely unmodified by the intervention of human technology. In other parts, ecosystems have been modified for long periods by aboriginal peoples before more-rapid transformation following colonization by Europeans. What then is to be called the "natural" state—pre-human or pre-European? The use of the term natural imposes a static perspective on restoration. Pickett et al. (1992) and Pickett & Parker (1994) have summarized recent changes in ecological paradigms away from the view of natural systems as static and predictable to one in which they are dynamic and constantly changing. Sprugel (1991) has discussed the difficulties in determining what the "natural" vegetation for a region should be, while Miller and Wigand (1994) have illustrated how complex the situation is for a specific study area in the southwestern United States. It may also be impossible to recreate past conditions because of extinctions and invasions. Even more important, the global environment is continuing to change, and it would seem naive to think we could restore a specified historical condition. This points to the futility of attempting to recreate a particular ecosystem as it was at a particular time (Simberloff 1990).

This view has been challenged by Aronson et al. (1995), who argue that some sort of reference ecosystem is needed as a goal for restoration efforts. The discussion in the literature on reference states is confused, however. Of course all restoration projects will have some form of ecosystem model to guide the restoration, based on which species are appropriate for the local site as determined by landforms, soils, climate, and so forth. But we consider that the definition of one particular natural state against which restoration success must be measured unnecessarily constrains restoration efforts and potentially leads to the setting of unattainable goals. Setting specific reference conditions as goals may be unrealistic if the reference system itself were the product of specific past environmental and management events, as discussed above. But using reference ecosystems to guide restoration planning can be useful so long as they are based on similar landform, soil, biotic, and climatic conditions (Norton 1991) and the range of potential conditions is recognized (see below). Aronson et al. (1995) argue that recent ideas on "the flux of nature" are fine in research circles but are potentially harmful in real-world restoration situations. We would argue that a failure to inject a dynamic perspective into real-world restoration efforts will inevitably lead to failed restorations and frustrated restorationists. The point is that many restoration projects are focused on unattainable goals relating to restoring some historic natural condition, an approach that is unrealistic, unachievable, and static. We need goals that are dynamic and that take into account the changing nature of the environment.

Success Criteria

A further aspect of the problem of knowing what we want to restore is knowing when we have reached our goal. At present there are few established criteria for success in ecosystem restoration, beyond catch-all statements on "restoring the natural ecosystem." Complete restoration of the natural system is probably an unachievable goal, as we have discussed, but we need to decide how close we should get. For each ecosystem attribute, there needs to be a clear set of thoughtfully defined objectives and goals for particular time periods. For instance, which attribute should we be most interested in—structure, function, or composition? How do we measure the redevelopment of these attributes for comparison with native ecosystems? How do these relate to natural successional processes? These questions have received some consideration but few useful generalizations have yet emerged. Some suggested measures include similarity indices between the re-

stored system and some reference system, the use of indicator taxa, and some estimate of system response in relation to resilience measures (Cairns 1989; Berger 1991; Westman 1991; Kondolf 1995; Kondolf & Micheli 1995).

An alternative approach that may be fruitful would be to utilize a range of structural, compositional, and functional measures, as is being proposed for estimating "ecosystem health" (Costanza et al. 1992) and the extent of ecosystem decline (Costanza 1992; Cairns et al. 1993). It may be possible to use these measures to assess ecosystem recovery. Ecosystem state can be assessed relative to the range of natural variability for a number of different parameters, as has been proposed for the measurement of ecosystem health in some North American forests (Fig. 4; Swanson et al. 1993; Caraher & Knapp 1995; Graham et al. 1995; Walker & Boyer 1995). This approach assesses current conditions against the estimated range of natural variability and can include any relevant parameters. It can be extended to the development of an "ecological reference template" that defines a limited range of states in ecosystem process and structural variables (Allen 1994). Allen (1994) also points out that there will be a set of process and structure states currently desired by society, and the aim should therefore be to direct the system towards that set, with the recognition that the set may change with changing societal values.

While these approaches aim to assess the success of ecosystem management, they could equally well be applied to restoration, where the aim is to return target parameters to a predetermined range. Thus, where restoration aims to restore the hydrologic balance, parameters may include runoff rates, rates of water table change, and so on. Where the restoration aim is to return an area to some sort of native ecosystem, parameters may include density of dominant plant species, structural diversity, recolonization by native fauna, and so on. Parameters that measure functional aspects or the reestablishment of biotic interactions could also be included, including presence of pollinators, development of a seed bank, and so forth. The list of "vital ecosystem attributes" for structure and function suggested by Aronson et al. (1993*a*) provides a good starting point for assembling a set of parameters to be monitored. The combined set of parameters measured provides a "scorecard" for the restoration effort (Fig. 4). Clearly, the development of adequate measures of restoration success will be facilitated by greater cross-fertilization between restoration ecology and other rapidly developing areas of ecology.

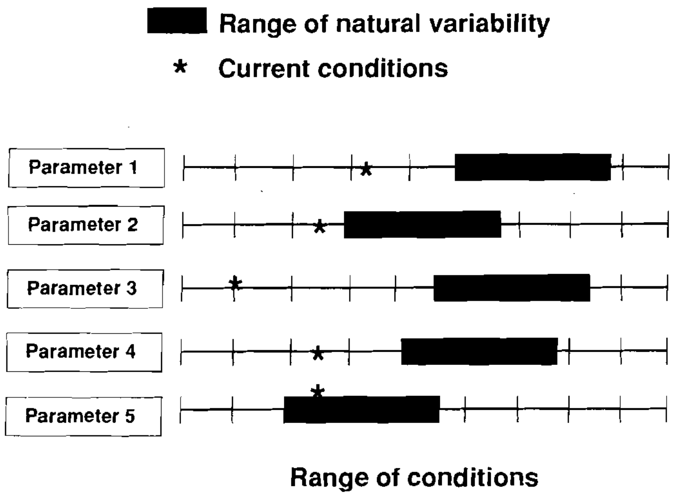

Figure 4. A restoration "scorecard" in which the current condition of a number of key parameters of the restored ecosystem is assessed relative to the estimated range of natural variability (from Caraher & Knapp 1995).

Restoration Methodologies

Luken (1990), in a discussion of succession management, highlighted three main procedures required to influence the course of succession or biotic development. These are also relevant in the context of restoration ecology. Pickett et al. (1987) observed that the three basic causes of succession are site availability, differential species availability, and differential species performance. From this, Luken proposed that these three factors could be regulated by using (1) designed disturbance to manipulate site availability, (2) controlled colonization to increase or decrease the availability and establishment of particular species, and (3) controlled species performance to decrease or increase the growth or reproduction of particular species.

Although the specific requirements for each of these actions vary from situation to situation, they provide a broad overview of what restoration aims to do. Disturbance of some kind will be required to prepare the site for establishment of the desired species. In some cases, the disturbance will have already occurred (as in minesites), and the restoration responds to this disturbance. In others, the disturbance may be required to force the jump from one metastable state to another—for instance, where non-native species prevent the regeneration of natives, the removal of the non-native species by fire, ploughing, or whatever may be necessary. Similarly, where structural decline of the soil has occurred, physical disturbance may be necessary to enhance seed germination and establishment. More-specific types of disturbance may be necessary to encourage germination of desired species—for instance, recent work has shown that large suites of species in Western Australia and elsewhere require contact with smoke to germinate (Dixon et al. 1995).

Colonization of a site following disturbance may occur naturally if a seed bank persists in the soil (Putwain & Gillham 1990; Bellairs & Bell 1993), but the availability, germinability and composition of this seed bank in relation to restoration goals needs to be assessed. Further colonization may be effected from surrounding areas, and it can be enhanced, especially if dispersal is by birds (McClanahan & Wolfe 1993; Robinson & Handel 1993). If neither soil seed stores nor dispersal into a site are effective in providing the required species mix, these have to be introduced to the site artificially, either as seed or as seedlings. A wide range of techniques for enhancing establishment success is available (Buchanan 1989; Leopold & Wali 1992; Harker et al. 1993), which mostly involve the provision of an adequate seed bed, ensuring the correct germination cues, and minimizing herbivory and interference from invasive species. These same techniques are important during the process of controlling species performances.

While the three processes identified by Luken (1990) are likely to be important, there are still some imponderables that have received little attention. First, as we have noted above, there is the potential for systems to follow alternative pathways depending on the precise combination of management, climatic, and biotic factors experienced. The stochastic nature of the environment means that the outcome of a particular restoration measure may differ when carried out at different locations or at different times. Similarly, we are only just beginning to understand the processes whereby ecological communities assemble. While there is considerable talk in the literature about deriving "assembly rules" (Drake 1990; Drake et al. 1993; Wilson et al. 1995), we are still a long way from being able to predict the outcome of adding species in particular combinations and orders.

Also of importance is a consideration of the importance of species other than plants in the restoration process. There is a general perception that the reintroduction of plants into an area will pull the remaining ecosystem components along with it. This is by no means clear. Indeed, it is likely that the other organisms are vital to the restoration process, particularly from the viewpoint of rendering the restored system viable in the long term. Of particular importance here are likely

to be the mycosymbionts (Allen, E. B. 1989; Allen, M. F. 1989), decomposer organisms, pollinators and, as discussed above, seed dispersers. Indeed, although the likely importance of fauna in the restoration process has been highlighted (Majer 1989), we are still far from appreciating or understanding its full significance.

Finally, Luken's approach deals only with one aspect of restoration, the return of structure and composition. As noted earlier, a variety of other ecosystem characteristics may be important to consider as restoration goals. Much less emphasis has been placed on ensuring that ecosystem processes are reinstated, although the persistence of the restored system ultimately depends on this (Aronson et al. 1993*a*, 1993*b*; Brown 1994).

Restoration at the Landscape Scale

We intimated earlier that restoration efforts need to focus less on individual sites and more on the landscape as a whole. This may be in the context of restoring landscape patterning or heterogeneity that have been altered by, for instance, changed disturbance regimes (Baker 1994), or in the context of increasing conservation values in extensively fragmented or modified landscapes. There is a clear need for guiding principles for restoration at this scale, and although a start has been made (Harker et al. 1993; Recher 1993; Saunders et al. 1993*b*; Saunders & Hobbs 1995; Whisenant 1995), there is considerable room for further development. An earlier analysis of the information available to guide landscape-scale activities revealed little that was directly translatable into guiding principles (Hobbs 1993).

Essentially, landscape design principles seem to have advanced little since the early, data-free suggestions by Diamond (1975) and Wilson & Willis (1975). These were developed in the context of reserve design but are equally relevant to the question of landscape-scale restoration. While there has been considerable debate over the principles put forward by these authors, the basic premises seem to have proven relatively robust: for example, bigger is better than smaller, connected is better than isolated. In this context, Hobbs (1993) has suggested that restoration at the landscape scale can be directly useful for conservation by providing additional habitat, by providing buffer zones, and by establishing corridors linking existing fragments. In many parts of the world, the extent of habitat loss means that it will not be possible to add further natural areas to the conservation estate because these areas simply do not exist. Restoration is therefore the only means available to address some of the gross under-representations of particular systems in networks of protected natural areas (Awimbo et al. 1995). Restoration can also provide buffers to mitigate the effects of external factors such as edge effects (Murcia 1995) and to link previously isolated fragments through the development of corridors (Hobbs 1992).

While these principles are broadly useful, they do not provide quantitative answers relevant to particular situations. Although we can say that "bigger is better" and "connected is better," we have no answer to the questions "How big does it need to be?" or "How connected does it need to be?" Work by Sisk & Margules (1993) and Andrén (1995) has started to provide information on how landscape geometry affects connectivity and the influence of edge effects. Similarly, Prober & Brown (1994) have demonstrated the minimum size of woodland patch that is likely to be viable in eastern Australia. Much remains to be done, however, to quantify the effects of different landscape configurations.

There is not likely to be one answer to these questions; much will depend on the objectives of the restoration. Thus, revegetation to modify the hydrological regime will require amounts and configurations of vegetation different than those required by restoration aimed at increasing faunal habitat. Beyond that, restoration for one species may need to be different from that for another, depending on

the life history and resource requirements of the individual species (Sparks et al. 1994). Thus, it becomes increasingly important to be clear about the goals of the restoration. If the goal is simply to increase the aesthetic quality of the landscape, it may be sufficient to assess the visual impact of any restoration activity (Forestry Commission 1992). On the other hand, restoration for functional or conservation practices has to take into account the relevant requirements for modifying the target function or providing habitat for the target species (or group of species). There is little evidence of this type of assessment being carried out in restoration projects, except in a few outstanding cases (Cox et al. 1994). In some cases it may be possible to nest the requirements of multiple species within one design. In others, difficult decisions about conservation priorities may have to be made.

Conclusion

We suggest that ecological restoration is becoming an essential component of both the management of production systems and the conservation of biodiversity. Recognition of the need for restoration does not deny the equally important need to retain adequate areas and examples of undegraded natural ecosystems (Loucks 1994). Indeed, these natural ecosystems provide a skeleton on which restoration activities are built. There are many sensible arguments as to why restoration activities should build on existing natural and remnant areas (Hobbs 1993). Restoration should therefore form part of an overall strategy for regional and local land management, rather than take place independently.

To date, most restoration ecology has focused almost entirely on the development of ad hoc methods, and what Medley (1994) has termed "an unattainable statement initiative: the recreation and maintenance of the spatiotemporal dynamics and functioning of an ecosystem." In other words, little overt consideration has been given to any of the key processes we have identified. The set of processes identified above provides the start of a general framework within which restoration projects can be planned and implemented. We recognize, however, that this requires further development and refinement, and we hope that our effort to produce such a framework will induce others to join in the process of refinement. We share the hope of Brown (1994) that "the artistry of restorations will give way to an applied science that has broader applicability, that learns quickly from the analysis of its mistakes, and that rapidly evaluates, verifies, disseminates, and revises concepts and ideas."

To become a useful tool in combating the continuous decline in production and conservation values across the globe, restoration ecology must also become a landscape-scale endeavor. We can no longer operate on a site-by-site basis but must grapple with the larger issues of ecosystem and landscape reconstruction. We by no means have all the answers in this sphere, but we must build on the framework we already have and work together to ensure that the restoration activities we undertake are not too little and too late.

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